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Testing the linearity of the response to combined greenhouse gas and sulfate aerosol forcing

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[1] Detection and attribution studies of the temperature response to anthropogenic greenhouse gases and tropospheric sulfate aerosol have relied on the assumption that the responses to each of these forcings add linearly. Using surface temperature from three ensembles of integrations of the second Hadley Centre coupled model (HadCM2) forced with observed changes in greenhouse gases alone, the direct effect of sulfate aerosol alone, and combined changes in greenhouse gases and sulfate aerosol, we test this assumption. We examine the residual, defined as the response to the combined forcings, minus the sum of the responses to the individual forcings, and compare its distribution with that of control variability. Considering both global mean changes and changes at each grid point, we find no evidence that the responses to greenhouse gases and sulfate aerosol combine nonlinearly in HadCM2. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1620 Global Change: Climate dynamics (3309); 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation. **Citation:** Gillett, N. P., M. F. Wehner, S. F. B. Tett, and A. J. Weaver (2004), Testing the linearity of the response to combined greenhouse gas and sulfate aerosol forcing, *Geophys. Res. Lett.*, *31*, L14201, doi:10.1029/2004GL020111.

1. Introduction

[2] One of the most basic assumptions underlying optimal detection as described, for example, by *Mitchell et al.* [2001], is the assumption that the response to the sum of two climate forcings is equal to the sum of the responses to the individual forcings. This assumption underlies studies, such as those of *Tett et al.* [1999], *Stott et al.* [2001], and *Tett et al.* [2002], which attempt to separately identify the response to greenhouse gases and anthropogenic sulfate aerosol. Complex climate models are not usually integrated in transient experiments with sulfate-only forcing, thus the magnitude of the sulfate response in observations is usually estimated using integrations forced with combined greenhouse gas and sulfate aerosol changes, and others with greenhouse gas changes only. This approach would be flawed, as indeed would all linear approaches to estimating the amplitude of greenhouse gas and sulfate signals, if the response to the sum of the two forcings were significantly different from the sum of the individual responses.

[3] Several authors have examined the more general question of whether the mean radiative forcing at the tropopause is a good predictor of the change in the annual mean global mean surface temperature over different forcing agents [e.g., *Cox et al.*, 1995; *Hansen et al.*, 1997]. Both these studies conclude that for greenhouse gases and sulfate aerosols this is generally so, but that regional and seasonal responses differ for different forcings. However, these experiments were carried out in equilibrium conditions, with relatively coarse-resolution GCMs. These results nonetheless indicate that the global mean response to these forcings is linearly additive, but that spatio-temporal patterns of response are different. It is these differences which allow greenhouse gases and sulfate aerosol to be separately detected [e.g., *Tett et al.*, 1999; *Mitchell et al.*, 2001], but these studies do not examine whether these responses are locally linearly additive.

[4] Several studies examining the issue of the linear additivity of greenhouse gas and sulphate aerosol responses were reviewed by *Ramaswamy et al.* [2001]. *Ramaswamy and Chen* [1997] examined changes in zonal mean surface temperature, using equilibrium simulations of the GFDL model coupled to a mixed-layer ocean model. They conclude that there is no evidence that the responses to greenhouse gas and sulfate aerosol add nonlinearly. *Haywood et al.* [1997] take this analysis further by examining changes in surface temperature in three transient integrations of the GFDL R15 coupled ocean-atmosphere model forced with greenhouse gas changes only, sulfate aerosol changes only, and combined greenhouse gas and sulfate aerosol changes. They compare the sum of the response to the individual forcings with the response to the summed forcings using maps of surface temperature changes, and they too conclude that the responses add linearly, though they do not test this statistically. *Penner et al.* [1997] also conclude that the equilibrium pattern of temperature response to a combination of greenhouse gas and sulphate aerosol forcing is the linear sum of the responses to the individual forcings, based on simulations of the NCAR CCM1. However *Penner et al.* [1997] also suggest that the global mean responses to the forcings do not add linearly in a transient integration, although no statistical tests are applied to this result. *Boer and Yu* [2003] demonstrate linear additivity of the response to greenhouse gas and sulphate aerosol forcing in CGCM1, which they hypothesize is explained by a fixed geographical pattern of local feedback processes. T. M. L. Wigley et al. (manuscript in preparation, 2004) examine the issue of the linear additivity of surface temperature response using some recent integrations of the Parallel Climate Model

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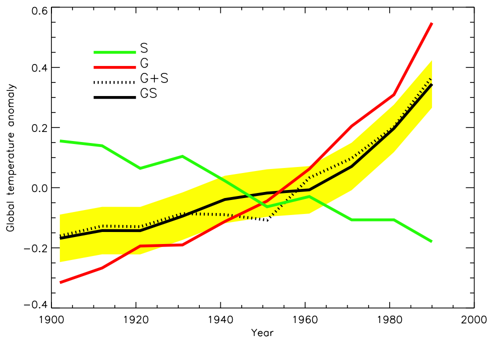

Figure 1. Global mean surface temperature anomalies (K) in ensembles of integrations of HadCM2 forced with combined greenhouse gas and sulfate aerosol changes (GS), greenhouse gas changes only (G), and sulfate aerosol changes only (S). The dotted line shows the sum of the responses to G and S. The yellow band shows the 5–95% significance range for differences between GS and G+S estimated from control variability.

(PCM). While the large range of ensembles integrated allows them to test the linearity assumption for a range of forcings, they find that the model has a non-stationary climate, and hence they need to make additional assumptions to test linear additivity. Globally averaged tropopause height changes, which represent vertically integrated temperature changes, also exhibit linear additivity in the response to anthropogenic and natural forcings including greenhouse gases and sulphate aerosols [*Santer et al.*, 2003].

[5] Although there is thus considerable evidence from a range of models that the responses to greenhouse gases and sulfate aerosol add linearly, other studies continue to suggest that this not the case. For example, *Levine and Berliner* [1999] state that interactions among forcings imply that the pattern of response to greenhouse gases and sulfate aerosol is not simply the sum of the responses to the two forcings. Recent two-dimensional modeling results also indicate that these responses may not add linearly (C. Forest, personal communication, 2002). Given that it is primarily high resolution coupled GCMs which have been used to separately detect greenhouse gas and sulfate aerosol influence [e.g., *Mitchell et al.*, 2001], it is important to check the linearity assumption in these cases. *Sexton et al.* [2003] show that the greenhouse gas and direct sulphate aerosol responses add linearly in an atmosphere-only GCM, but they find weak departures from linear additivity of the greenhouse gas and indirect sulphate aerosol responses. *Feichter et al.* [2004] use an atmospheric model with a coupled sulfur cycle and a mixed layer ocean to investigate the linear additivity of the response to greenhouse gas and sulfate aerosol. They identify departures from linear additivity in the temperature response, suggesting that the indirect sulfate and greenhouse gas responses may not exhibit linear additivity. No integrations including the indirect effect of sulphate aerosol are available for HadCM2, and therefore we could not test this result in the context of a coupled model. While a future study including such effects might be desirable, the results presented here, based on the direct sulphate aerosol effect only, are relevant to the majority of models used for detection by the IPCC [*Mitchell et al.*, 2001].

2. Method

[6] We use three ensembles of integrations of the second Hadley Centre Coupled model [*Johns et al.*, 1997]: a four-member ensemble forced with greenhouse gas increases only (G), a four-member ensemble forced with direct sulfate aerosol changes only (S), and a nine-member ensemble forced with greenhouse gas and sulfate aerosol changes (GS). The G and GS ensembles are the same as those used by *Tett et al.* [1999] and *Stott et al.* [2001], except for the addition of five GS ensemble members, and the S ensemble was integrated separately at the Lawrence Berkeley National Laboratory. We also use a 1710-year control integration for significance testing. As in *Tett et al.* [1999], the change in sulfate aerosol was represented in the model by a change in surface albedo.

3. Results

[7] Figure 1 shows the ensemble mean global mean temperature anomaly in each of the three ensembles. As might be expected, the global mean temperature falls by ~0.3 K over the century in the sulfate only ensemble, and increases by ~0.9 K in the ensemble with greenhouse gas forcing. The dotted line showing the sum of the anomalies in the G and S ensembles lies close to the GS ensemble mean. In fact this residual is never significantly nonzero, based on a two-tailed t-test at the 10% level. We estimate the standard deviation of this residual here and elsewhere by scaling that of the control by $\sqrt{1/9 + 1/4 + 1/4}$ to allow for averaging over ensemble members. Thus as in previous studies, we too find no evidence that the global mean responses add nonlinearly.

[8] Figure 2a is a map of temperature trends over the period 1896–1996 in the ensemble forced with changes in greenhouse gases and sulfate aerosols. Figure 2b shows the sum of the trends in the ensembles forced separately with greenhouse gases and sulfate aerosols. As *Haywood et al.* [1997], *Penner et al.* [1997] and *Boer and Yu* [2003] conclude for other models, these patterns appear very similar, suggesting that the responses are linearly additive. However, it is hard to be sure about this result, without the application of any statistical tests.

[9] We calculated a t-statistic for the residual trend at each grid point (G+S-GS), using a standard deviation estimated from control variability. If there were a significant residual, we would expect these t-statistics to be significantly non-zero. Since there is one such t-statistic for each grid point, we plot a histogram, shown in Figure 3. The theoretical Student's t-distribution, and the distribution calculated from control variability are shown for comparison. The t-statistics of the residual trend are not significant, indicating that the residual is not significant compared to control variability. We also summed the squares of the residual trends to give an F-statistic of 0.724. This, too, is not significant.

[10] Finally, given that these results are used in the context of optimal detection, we applied a regression-based method to this model output. Using the detection methodology of *Allen and Stott* [2003], we regressed surface

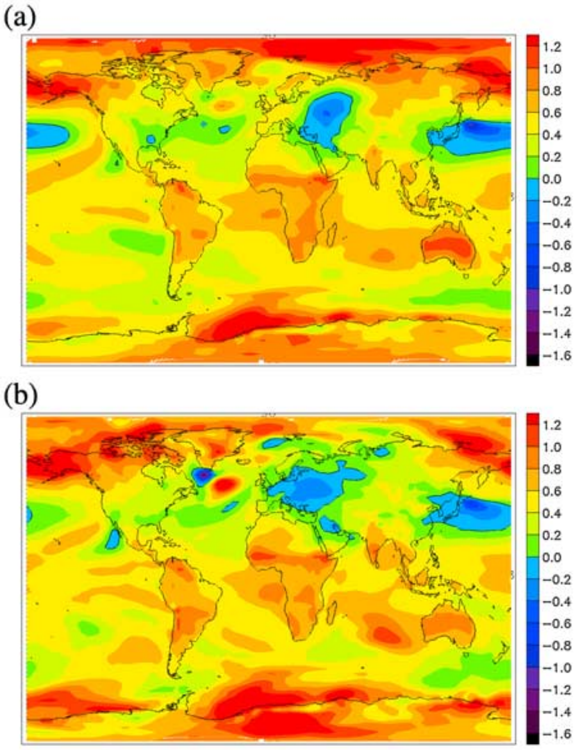

Figure 2. Ensemble mean surface temperature trends (K/year) over the period 1896–1996 in (a) a greenhouse gas and sulfate aerosol forced ensemble of HadCM2 and (b) the sum of the trends in ensembles forced separately with greenhouse gas changes and sulfate aerosol changes. The difference is not significant, based on a comparison of its F-statistic with control variability.

temperatures from the GS ensemble onto those from the G and S ensembles, using a 10 EOF truncation, and a total least squares estimator (this takes into account sampling uncertainty in the G and S patterns, and gives an unbiased regression coefficient). Figure 4 shows the resulting confidence ellipse. The fact that greenhouse gas and sulfate aerosol amplitudes are both consistent with one reconfirms

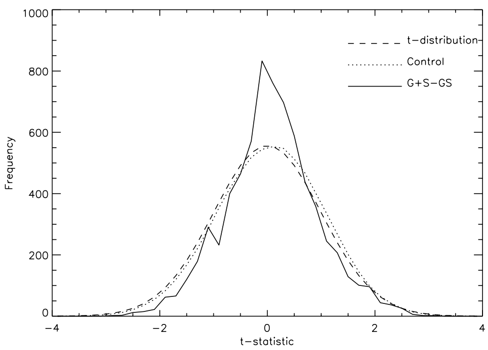

Figure 3. Histogram of t-statistics of grid point residual trends (G+S-GS) calculated with respect to control variability. The distribution calculated using control segments, and the theoretical t-distribution are plotted for comparison. Based on the F-statistic the residuals are not significantly different from control variability.

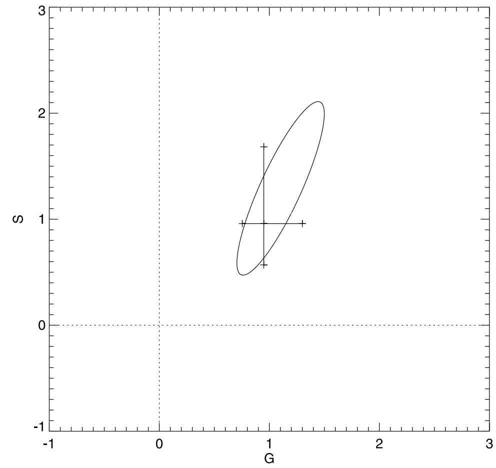

Figure 4. Regression coefficients from a two-way regression of the GS response onto the G and S responses. A five decadal mean (1946–1996) T4 spherical harmonic diagnostic of surface temperature with a 10 EOF truncation was used as in detection studies. Uncertainty bars show one-dimensional 5–95% confidence ranges, and the two-dimensional 90% confidence region is shown as an ellipse. The confidence ellipse includes (1, 1) which indicates that the GS response is consistent with G+S. Residuals in the regression were consistent with control variability.

our result that the GS response is consistent with a linear sum of the responses in the G and S runs. Applying the residual test of *Allen and Tett* [1999], we found no evidence that the residual in the regression (GS-G-S) was inconsistent with control variability.

4. Conclusions

[11] Many climate change detection studies make the assumption that the responses to greenhouse gas and sulfate aerosol changes add linearly [e.g., *Mitchell et al.*, 2001; *Tett et al.*, 1999]. However, some authors have suggested that such an assumption may not be valid [e.g., *Levine and Berliner*, 1999], and others find that it is not valid in simpler models (C. Forest, personal communication, 2002). Using three separate ensembles of transient integrations of a coupled climate model with no climate drift, we find no evidence that the temperature responses to greenhouse gases and direct sulfate aerosol effects add nonlinearly. We examine changes in the global mean and linear trends at each grid point over the 20th century, and find in both cases no evidence that the linearity assumption is violated. Lastly we regress the response to the combined forcings onto the individual model-simulated response patterns, and again find no evidence for nonlinearity. Other studies using models without coupled oceans have found that the responses to greenhouse gases and the indirect sulfate effect may add nonlinearly [*Sexton et al.*, 2003; *Feichter et al.*, 2004], thus we suggest that a similar study should be performed in the future with transient integrations of an ocean-atmosphere model incorporating the indirect sulfate effect.

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